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13. ABSTRACT (Maximum 200 words)

1. Foreword

Following is the Center for Imaging Science (CIS) final report for 1999-2001 on the development of the fundamental underpinnings for the representation and understanding of complex scenes. CIS is composed of researchers from MIT, Ohio State, Smith-Kettlewell Eye Research Institute, University of Illinois, University of Texas at Austin, University of Texas at El Paso, Washington University and Yale. Reflecting the broad nature of imaging science, the research in at CIS is multidisciplinary encompassing physics, mathematics, electrical engineering, computer vision, computer science and cognitive science.

The efforts of CIS during the 1999-2001 years built on the mathematical foundations that have been emerging over the past several decades. Examining a broad class of remote sensing problems, we have been establishing the fundamental framework for the inference and representation of structures in complex systems and scenes of complex shapes proceeding from the representation of complex scenes, to image formation and sensor modeling, and culminating in the development of the fundamental underpinnings for optimal decision/recognition strategies in image understanding and ATR. Within this framework, we are establishing the methodology for establishing the limits of performance of detection, identification and recognition algorithms solving remote sensing problems involving data from multiple active and passive sensors.

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December 12, 2001

Dr. David Skatrud
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Research Triangle Park, N.C. 27709-2211

Dear David:

Enclosed is the Final Report on ARO award DAAD19-99-1-0012.

Sincerely,

Michael I. Miller
Director

MIM:dk
Enclosure

REPORT DOCUMENTATION PAGE (SF298)
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2. Table of Contents (if report is more than 10 pages) N/A

3. List of Appendixes, Illustrations and Tables (if applicable) N/A

4. Statement of the problem studied

These have been extremely productive years including numerous publications, talks, visits to Army Laboratories, database developments, and distribution to Academic and government researchers, and community service. Contributions are in the 5 major thrust areas that CIS is pursuing:

1) Fundamental Bounds and Metrics for Detection/Tracking/ Identification;
2) The Infinity of Variation in FLIR/Optical and Radar Signatures;
3) Multiple Sensor Fusion and Information Theory;
4) Information Theory Based Complexity of Representation and Compression, and
5) Databases and Clutter: Collection and Characterization. Results include: derived bounds for aimpoint across scale; derived bounds for aimpoint in clutter; derived bounds for aimpoint using LADAR/FLIR; and derived bit rate information bounds for VIDEO sensor.

The Web site continues to receive 5000-7000 visitors a month and has distributed databases to an average of 500 unique visitors each month. CIS members have submitted for publication 6 papers, published 34 papers, gave 32 talks, and have been involved in numerous meetings with the Army and DOD. CIS has a publications index of 253 papers in the areas of target recognition, deformable geometry, image formation and sensor modeling, tomographic imaging, computational vision, inference and optimization, adaptation and learning, multiple sensor fusion, clutter modeling, and performance bounds.

5. Summary of the most important results

The major results in the Center:

1. Performance bounds and metrics: We have established Performance Bounds and Metrics for pose estimation and identification. We have established for pose the MMSE estimator, and established curves of performances for multiple sensors, FLIR, LADAR, HRR, VIDEO.

   We have established the tight connection between estimator bounds and ID bounds. Exponential ID bounds are determined by estimator accuracy bounds.

2. Sensor fusion: We have established the optimum methodology for combining information optimally from multiple sensors. Estimation and ID bounds have been calculated for combinations of HRR, LADAR, and FLIR.

3. FLIR signature variation: We have established a methodology for accommodating the infinity of signature variation in FLIR associated with temperature variability due to whether and tank operating conditions. We have demonstrated that for Comanche FLIR the uncertainty of signature costs approximately 1/2 bit of accuracy in estimation.

4. Clutter: We have established the fundamental role of higher order statistics such as kurtosis plays in the degradation in performance of ATR systems.

5. Databases: We have established a Nation repository for DoD databases from which investigators around the world can access military data sets. (see http://cis.jhu.edu)

Given in the appendix is a detailed description of the work and results in the Center for Imaging Science.

6. Listing of all Publications supported under this grant.

a. Papers Published in peer-reviewed journals

J.P. Havlicek, D.S. Harding and **A.C. Bovik**, "Multidimensional quasi-eigenfunction approximations and multicomponent AM-FM models," IEEE Transactions on Image Processing, vol. 9, no. 2, pp. 227-242, February 2000.

N. Damera-Venkata, T.D. Kite, W.S. Geisler, B.L. Evans and **A.C. Bovik**, "Image quality assessment based on a degradation model," IEEE Transactions on Image Processing, vol. 9, no. 4, pp. 636-650, April 2000.

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A. Srivastava , U. Grenander, G. R. Jensen, **M.I. Miller**, "Jump-Diffusion Markov Processes on Orthogonal Groups for Object Recognition," *Special Issue of the Journal of Statistical Planning and Inference, November, 2001.*

M.I. Miller and L. Younes, "Group Actions, Homeomorphisms, and Matching: A General Framework," *International Journal of Computer Vision, Volume 41, No 1/2, pages 61-84, January, 2001.*

Joseph O'Sullivan, Michael D. DeVore, Vikas Kedia, **M. I. Miller**, "SAR ATR Performance Using a Conditionally Gaussian Model," *IEEE Transactions on Aerospace and Electronic Systems, 37 No. 1, Page 91-108, January, 2001.*

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R. E. Blahut, **J. A. O'Sullivan**, and D. L. Snyder, ``Information Theoretic Imaging," invited paper for the special issue of the *IEEE Transactions on Information Theory} in honor of the 50th anniversary of C. E. Shannon's 1948 paper, vol. 44, no. 6, pp. 2094-2123, October 1998. Also in* Information Theory: 50 Years of Discovery, S. Verdu and S. W. McLaughlin, Eds., pp. 50-79, 2000.

Miguel Hernandez, **D. H. Williams**, "Simulation of Localized Atmospheric Obscurants in Graphical Images," 2000 International Conference on Imaging Science, Systems and Technology (CISST'2000), Las Vegas, NV, June 26-29, 2000, pp 533-537.

A. L. Yuille, J. M. Coughlan, Y. N. Wu, and **S. C. Zhu,** "Order Parameter for Detecting Target Curves in Images: How Does High Level Knowledge Helps?", *Int'l Journal of Computer Vision, vol. 41, No. 1/2,* pp.9-33, January, 2001.

S. C. Zhu, X. W. Liu and Y. N. Wu, "Exploring Texture Enesmbles by Efficient Markov Chain Monte Carlo" --- Toward a "trichromacy" theory of texture, IEEE Trans. on Pattern Analysis and Machine Intelligence, vol. 22, No. 6, June, 2000.

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b. Papers published in non-peer reviewed journals or in conference proceedings

Anuj Srivastava, "Bayesian Filtering for Tracking Pose and Location of Rigid Targets." In proceedings of SPIE Aerosense, Orlando, FL, April 2000.

Anuj Srivastava, "A Nonlinear Filtering Method for Geometric Subspace Tracking," IEEE Sensor Array and Multichannel Signal Processing Workshop, Boston March 2000

Olga Kosheleva, Carlos Mendoza, **Dr. Sergio D. Cabrera**, "Segmentation-Adaptive DCT-based Compression and Evaluation on FLIR Images," Proc. SCI2000/ISAS2000 Conference, Orlando, FL, July 2000

S. H. Chan, A. E. Brito, and **S. D. Cabrera**, "Imposed Window Estimate for Adaptive Extrapolation of Complex Sinusoids in Gaussian Noise." Proc. 9th IEEE DSP Workshop (DSP2000), Hunt, TX, October 2000.

E. Whittenberger, A. E. Brito, and **S. D. Cabrera**, "EigenSMD and FisherSMD Based Classification in Circuit Board Inspection," Procs. of World Multiconference on Systems, Cybernetics and Informatics (SCI2000), Orlando, FL., July 2000.

N. A. Schmid and **J. A. O'Sullivan**, ``Performance Analysis in ATR from Dimensionality Reduction," submitted to the IEEE 2000 International Symposium on Information Theory, Sorento, Italy, June 2000.

P. Moulin and **J. A. O'Sullivan**, ``Information-Theoretic Analysis of Information Hiding," submitted to the IEEE 2000 International Symposium on Information Theory, Sorento, Italy, June 2000.

N. A. Schmid and **J. A. O'Sullivan**, ``Method for Reducing Dimensionality in ATR Systems," submitted to SPIE Automatic Target Recognition X, Firooz A. Sadjadi; Ed., Orlando, April 2000.

M. D. DeVore, A. D. Lanterman, and **J. A. O'Sullivan**, ``ATR Performance of a Rician Model for SAR Images," submitted to SPIE Automatic Target Recognition X, Firooz A. Sadjadi; Ed., Orlando, April 2000.

J. A. O'Sullivan and M. D. DeVore, ``Performance-Complexity Tradeoffs for Several Approaches to ATR from SAR Images," submitted to SPIE Algorithms for Synthetic Aperture Radar Imagery VII, Edmund G. Zelnio; Ed., Orlando, April 2000.

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Alan Yuille, J. Coughlan, and S. C. Zhu, "Order Parameter Theory: How Does High Level Knowledge Helps?" Proc. of Int'l Conf. on Computer Vision and Pattern Recognition, 2000.

A.L. Yuille, J.M. Coughlan, and S. Konishi, "The Generic Viewpoint Constraint Resolves the Generalized Bas Relief Ambiguity".. In Proceedings 200 Conference on Information Sciences and Systems
(CISS 2000). Princeton University. March 15-17. 2000.

S. C. Zhu, R. Zhang, and Z. W. Tu, "Integrating Top-down/Bottom-up by Data Driven Markov Chain Monte Carlo for Object Recognition," Proc. of Int'l Conf. on Computer Vision and Pattern Recognition, 2000.

S. C. Zhu, X.W. Liu, "Learning in Gibbsian Feilds: How Accurate and How Fast can It Be?" Proc. of Int'l Conf. on Computer Vision and Pattern Recognition, 2000.

c. Papers presented at meetings, but not published in conference proceedings

Dmitri Bitouk, Ulf Grenander, **Michael I. Miller**, Paritosh Tyagi, "Fisher information in transported generator clutter models," *AeroSense 2001: Automatic Target Recognition XI, SPIE Proceedings, vol. 4379, 2001.*

M. I. Miller, "The Future of Computational Imaging Science," Brown Hall, Washington University, Donald L. Snyder Workshop, January 2000, invited.

M. I. Miller, Symposium Speaker, "Computational Anatomy: An Emerging Discipline" at the University of Georgia's The Bernoulli Society, Symposium on Inference for Stochastic Processes, May 2000, invited.

M. I. Miller, Panel Presenter, ISP workshop at the University of Colorado, August 6, 2000, invited.

M. I. Miller, Speaker, "ATR: Automated Target Recognition," at the Thomson-CSF Research Laboratory in Palaiseau, France, September 28, 2000, invited.

M. I. Miller, Speaker, at the Mathematics and Image Analysis 2000 in Paris, September 27, 2000, invited.

M. I. Miller, Visiting Lecturer, Ecole Normale Superieure de Cachan, Paris, France, September – October 2000, invited.

M. I. Miller, Speaker, "Computational Anatomy: An Emerging Discipline," at Institute for Mathematics and Its Applications (IMA) University of Minnesota's Symposium on Brain Imaging, October 13, 2000, invited.

M. I. Miller, Colloquium Speaker, "Deformable Templates and Image Understanding" at the Applied Physics Laboratory, March 2000, invited

M. I. Miller, "The Information Theory of ATR in the 21st Century," Crystal Forum, Crystal City Marriott, Automatic Target Recognition...Making Weapons Smart, Sponsored by the Deputy Under Secretary of Defense for Science and Technology and the DoD Automatic Target Recognizer Working Group, April 17, 2000.

M. I. Miller, "Image and Information Understanding Via Pattern Theoretic in Variances," at the "Pattern-Based Computation Workshop," sponsored by DARPA in La Jolla, CA, October 24-27, 2000, invited.

R. Labiaga and **D. Williams**, "A Load Balancing Technique for Heterogeneous Distributed Networks" , 2000 International Conference On Parallel and Distributed Processing Techniques, and Applications (PDPTA'2000), Las Vegas, Nevada

S. C. Zhu, 2001 Bayes Vision Workshop, San. Francisco, CA.

S. C. Zhu, The Abdus Salum International Centre for Theoretical Physics, Italy, (Teaching Short Courses), 2000.

S. C. Zhu, Institute for Mathematics and its Applications, 2000.

S. C. Zhu, Microsoft Research, Beijing, 2000.

S. C. Zhu, Pattern Theory Seminar, Brown University, 2000.

S. C. Zhu, AI seminar, Carnegie Mellon University, 2000.

d. Manuscripts submitted, but not published

Anuj Srivastava, U. Grenander, "Probability models for Clutter in Natural Images," submitted to IEEE Transactions on Pattern Analysis and Machine Intelligence July 2000

Anuj Srivastava, Eric Klassen "Geometric Filtering for Subspace Tracking," submitted to IEEE Transactions on Signal Processing June 2000

J. A. O'Sullivan, ``Properties of the Information Value Decomposition," submitted to the IEEE 2000 International Symposium on Information Theory, Sorento, Italy, June 2000.

P-Y. Burgi, A.L. **Yuille** and N.M. Grzywacz, "Probabilistic Motion Estimation Based on Temporal Coherence" Neural Computation. In press. 2000.

A.L. Yuille, J.M. Coughlan, Y-N. Wu and S.C. Zhu, "Order Parameters for Minimax Entropy Distributions: When does high level knowledge help?" Accepted by Computer Vision and Pattern Recognition. CVPR'2000. 2000.

S. Konishi and **A.L. Yuille**, "Statistical cues for Domain Specific Image Segmentation with Performance Analysis." Accepted by Computer Vision and Patern Recognition. CVPR'2000. 2000.

7. **Scientific personnel**

J. K. Aggarwal, University of Texas at Austin
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Donald L. Snyder, Washington University
David H. Williams, University of Texas at El Paso
Alan Willsky, MIT
Alan L. Yuille, Smith-Kettlewell Eye Research Institute
Song-Chun Zhu, Ohio State University

8. **Report of inventions – Technology Transfer**

System for Image Compression and Decompression, Inventors **M.I. Miller**, A. Polsky, Filed May 2001, May 2001

Method and Apparatus for Processing Images with Curves, Filed January 27,2000, Inventors M. Bakircioglu, N. Khaneja, **M.I. Miller**, January 2000

Method and Apparatus for Image Registration Using Large Deformation Diffeomorphisms on a Sphere, Inventors M. Bakircioglu, S. Joshi, **M.I. Miller**, Filed December 27,2000, December 2000

Method and apparatus for image registration, **M.I. Miller**, G.E. Christensen, S.C. Joshi, U. Grenander, Assignee: Washington University (St. Louis, MO), Application No. 678628, December 1999

Method and Apparatus for Cross-Modality Image Registration, Inventor **M. I. Miller**, Filed December 11, 2000, January –1

9. **Bibliography N/A**

10. **Appendices**

Final Report from Subcontractor University of Texas Austin

Johns Hopkins University Subcontract

Army Research Office / Center for Imaging Sciences DAAD-19-99-1-0012

Final Report – UT Austin (Profs. Aggarwal, Bovik & Ghosh)

August 31, 2001

Summary of the Most Important Results.

Region/Edge-based Target Segmentation of FLIR Images Modeled by Weibull/Gaussian Distributions. An initial detection algorithm employing Gaussian and Weibull functions to model the background is used to robustly identify all possible regions in the image that are candidate locations of targets [1]. A two-stage focused analysis of each candidate target location is then performed to get an accurate representation of the target boundary. A region-growing procedure that uses a diffusion process driven by the underlying probability distribution of the background and modulated by local shape changes of the target is used to estimate the target shape. The boundary of the target is then combined with salient edge information in the image to arrive at a more accurate representation of the target boundary. A computationally efficient and flexible method to incorporate the salient edge information into the region boundary has been developed by formulating it as a Bayesian classification problem. Finally, to reduce the false alarm rate, a higher-level interpretation module is used to classify the detected areas as man-made or natural objects using geometric and FLIR intensity-based features extracted from the target.

Bayesian recognition of targets by parts in 2nd generation FLIR images. We have developed a hierarchical recognition strategy for classification and recognition of 2D targets in 2nd generation FLIR images that uses salient object parts as cues for recognition [2]. At the lowest level, classifiers are trained to recognize the class of an input object, while at the next, classifiers are trained to recognize specific objects. At each level, objects are recognized by their parts. Each classifier is made up of modules, each of which is an expert on a specific part of the object. Each modular expert is trained to recognize one part under different viewing angles and transformations. A Bayesian realization has been developed in which the expert modules present the probability density functions of each part, modeled by a mixture of densities to incorporate different views (aspects) of each part. Recognition relies upon the sequential presentation of the parts to the system without the use of any information on relationships between the parts. Part modules are given selective importance in the recognition process based upon how discriminating they are in the recognition process. Recognition results are obtained using a recursive Bayesian updating rule. The advantage of such a system is its ability to sequentially examine different parts of an object and modify the recognition probability as more parts are seen. Since each part is represented by an expert module, recognition is faster than when using a matching algorithm, and pose estimation is simplified. We have also developed a new method to decompose a target into its parts using its outline or boundary. This is based on the premise that different parts of an object show up as distinct surfaces in the image. By finding these surfaces, the parts of the target can be determined. To obtain these surfaces, cues such as edges, corner parts, and T-junctions, that suggest the existence of a surface are determined from the target's outline. A linear diffusion approach is used to determine the surface segments from the sets of cues. Segments are then grouped into parts. In the case where the underlying distribution of parts is not readily obtainable, neural network techniques may provide a

suitable alternative. The methodology for recognition by parts could easily be extended to 3D objects. If 3D parts were represented using primitives such as cylinders, hyperellipsoids, etc., the dimension of the shape feature will be much lower than is required for 2D objects.

Experimental results on 1,930 FLIR images showed that our automatic target detection/ recognition system can achieve recognition with a high degree of accuracy and a low false alarm rate [3]. Outdoor field FLIR images were used as input, in which the military targets were at a distance of 2- 3.5 kilometers from the sensor and thus occupied <5% of the image pixels. A total of 1,930 images from 28 datasets was used, ranging in quality from poor to good to excellent. All images were obtained under various ambient scene and weather conditions. 89% of the targets were correctly located in the detection stage, with a false alarm of <5%. 90% of the detected regions could be correctly segmented. For most datasets, 70% of the target types were correctly reported, with an 80% rate of pose recognition.

Detecting Moving Objects in Airborne FLIR Sequences. We have developed a methodology to detect independently moving objects in FLIR image sequences taken from an airborne, moving platform [4-6]. Ego-motion effects are removed through a robust multi-scale affine image registration process. Consequently, areas with residual motion indicate object activity. These areas are detected, refined and selected using a Bayesian classifier. The remaining regions are clustered into pairs. Each pair represents an objects front end or rear end. Using motion and scene knowledge we estimate object pose and establish a region-of-interest for each pair. Edge elements within each region of interest are used to segment the convex cover containing the independently moving object. Our experiments used real, complex cluttered and noisy sequences.

This robust system is designed for integration into a comprehensive automatic target recognition (ATR) and action classification system. This dynamic scene analysis system could be integrated into existing static image ATR systems. It could be used in a Bayesian sensor fusion paradigm to improve detection accuracy and reduce false alarms. In such a fusion stage, detection, recognition and pose results from cues (such as motion, target shape, size or parts) could be integrated using a Bayesian meta-classifier. The different paradigms could be used to mutually verify results and synergetically improve performance. Compared to existing systems, dynamic scene analysis enables the inclusion of target action recognition. This action recognition could enable the automatic extraction of multi-frame analysis results, such as object starts and stops or changes in acceleration or direction.

3D Reconstruction of an Urban Scene from Synthetic Fish-eye Images. Fish-eye stereo analysis has many promising applications in multisensor computer vision. We have explored the feasibility of generating a 3D model of an urban scene from a pair of stereo images taken by full-circular fisheye lenses from different views [7]. Similar to the stereo analysis of pinhole camera images, methods for establishing correspondence and triangulation recovery must be adapted to the nonlinear fish-eye transformation model. Our reconstruction algorithm is based on an error-free equi-distance projection model. Our algorithm was tested on synthetic data.

Structure in Content-based Image Retrieval.. We have studied the use of structure in content-based image retrieval (CBIR) with those based on histogram and texture analysis methods in the context of locating images containing manmade objects. The advantage of using structure in such queries was demonstrated by analyzing an image database of monocular grayscale outdoor images to retrieve images

containing buildings [8]. A methodology based on the principles of perceptual grouping in a Bayesian framework has been developed [9]. Higher-level and lower-level vision methodologies have been combined for enhanced performance [10]. A lower-level analysis module is used to increase the capability of the higher-level module. Higher-level analysis is performed globally to extract structure using the principles of perceptual grouping to extract different shape representations for higher-level feature extraction from primitive image features. Lower-level analysis is performed globally using Gabor filters to extract texture features. A manmade object region of interest is used as a frame for conducting lower-level analysis, although such analysis is not confined to the region of interest. A channel energy model is utilized to extract lower-level feature vectors consisting of fractional energies in various spatial channels. The results obtained by the higher-level analysis level using a Bayesian classifier were refined and enhanced by the results obtained by the lower-level analysis module using a nearest neighbor classifier. Experimental results document the enhanced recall and precision rates obtained using this combined approach.

It has been noted that many of the perceptually salient image properties, such as collinearity, parallelism, and line continuation, are viewpoint invariant. Certain scene structures will always produce images with discernable features, regardless of viewpoint, while other scene structures virtually never produce these properties. This correlation between salience and invariance has suggested that the perceptual salience of viewpoint invariance is due to the leverage it provides for inferring geometric properties of objects and scenes. The perceptual inference and grouping process and color histogram are *isotropic* mappings that are invariant to the isometries of geometrical objects. Isotropic mappings, acting on isometries of perceptually salient structures, are useful in image retrieval as they illustrate the similarity of structures present in different images. *Anisotropic* mappings, such as texture analysis response obtained from a channel energy model, can determine image uniqueness. The premise of our model, which is consistent with the functionings of the human visual system, is to extract rich descriptions of lower-level anisotropic local image structure, and use these descriptions for subsequent grouping into higher-level isotropic features.

The latest implementation of the system [11-13] is able to serve queries ranging from scenes of purely natural objects such as vegetation, trees and sky, to images containing conspicuous structural objects such as buildings, towers and bridges. The system was tested on an image database consisting of 2660 24-bit color images. When tested on a query image of a flower, the system successfully eliminated images that contained significant manmade structures even when they had similar color distribution and/or texture patterns, and retrieved only images that also contained flowers, leaves and grass. Likewise, a query image of a building façade retrieved images similar in both lower-level vision content (histogram and texture patterns) and higher-level vision content (semantics describing structure). The results emphasize the efficacy of using a combination of isotropic and anisotropic features.

Visualization and Classification of High-Dimensional Data Using Nonlinear Manifolds. This is a fundamental problem in object recognition and image analysis. Our seminal work and breakthrough in this area appeared as a 22 page paper in *IEEE Transactions on Pattern Analysis and Machine Intelligence* in January 2001 [14]. We first modified the most well known non-linear manifolds, namely, the principal curve and principal surface [15]. The modification involves orienting and clipping the covariances at each of the manifold nodes such that variances in directions tangential to the manifold are minimized. The motivation behind this modification lies in the desire to recover and approximate the projection step of the

original principal curve algorithm in current probabilistic principal surface formulations. Experiments on artificial and real datasets suggest that this modification does indeed lead to a vast improvement in convergence speed and better generalization properties for principal surfaces. Subsequently, we pioneered the use of spherical manifolds for the simultaneous classification and pose estimation of 3-D objects from 2-D images [16]. The spherical manifold imposes a local topological constraint on samples that are close to each other, while maintaining a global structure. Each node on the spherical manifold also corresponds nicely to a pose on a viewing sphere with 2 degrees of freedom. The proposed system has been successfully applied to tank and aircraft classification and pose estimation.

Modular Learning Through Output Space Decomposition, with Applications to Classification of Hyperspectral Sensor Data. Several recognition problems pertinent to ARO involve a large number of potential classes. In addition, some of the new sensors - most notably hyperspectral sensors that provide about 200 spectral bands per "pixel", and is being rapidly deployed in several DoD remote sensing and surveillance applications – have the additional challenge of high-dimensional input space. While feature selection/extraction techniques are often used to simplify the input space and alleviate the curse of dimensionality, modular learning paradigms based on the divide and conquer precept are used to decompose the problem into simpler classification tasks through input space, training set or feature space decomposition. We have developed in detail an output-space decomposition framework in which a C>2 class problem is systematically decomposed into simpler two-(meta)class problems [17-21]. Apart from improving generalization performance for difficult classification problems, such problem decomposition in output space allows class specific feature extraction, and yields significant domain knowledge that is not possible to obtain from conventional single classifiers or modular learning paradigms.

Two frameworks for problem decomposition in output space were developed. In the first framework, called the *Pairwise Classifier* (PC) framework, a C-class problem is exhaustively decomposed into a set of C choose 2 two-class problems [18]. Features that best discriminate the two classes are extracted for each pairwise classifier and the outputs of all these classifiers are combined to yield the final output in the original output space. The PC framework is applied to the problem of landcover prediction involving high dimensional hyperspectral sensor data that can be treated as a signal with high correlation among adjacent spectral bands. Top-down and bottom-up multiresolution feature extraction algorithms for such specialized sensors are also developed for two-class problems. Used in conjunction with the PC framework, these feature extraction algorithms yielded significant improvements in classification accuracy and discovery of useful domain knowledge consistent with experts' opinion, for a variety of datasets [21, 17].

The second framework for problem decomposition in output space [20], called the *Binary Hierarchical Classifier* (BHC) framework, involves the decomposition of a C-class problem into a binary tree with C leaf nodes and C-1 internal nodes. Each internal node is comprised of a feature extractor and a classifier that discriminates between the two meta-classes represented by its two children. Both bottom-up (BU-BHC) and top-down (TD-BHC) approaches for automatically building such a BHC are developed. The BU-BHC is built by applying agglomerative clustering to the set of C classes while the TD-BHC is built by recursively partitioning a set of classes at any internal node into two disjoint groups or meta-classes. The coupled problems of finding a good partition and of searching for a linear feature extractor that best discriminates the two resulting meta-classes are solved simultaneously at each stage of the recursive algorithm. The BHC framework not only reduces the number of two-class classifiers from C-choose-2 in the PC framework to only C-1, but it also discovers domain knowledge with regard to the class taxonomy

and the features that discriminate classes at each internal node. For difficult high dimensional classification problems, a significant improvement in classification accuracy over conventional classifiers is also obtained by the BHC classifiers [20]. A full paper detailing this approach and its successful application to a wide variety of pattern recognition problems is being prepared for PAMI.

Visualization of RBF Networks. RBF networks are one of the most powerful and popular neural network models, and have numerous applications of interest to ARO. A major problem with neural network models is the lack of interpretability. So we have devised a powerful method for the 3D visualization of the structure of radial basis function networks [22]. This method allows the visualization of basis function characteristics (centers and widths) along with second level weights. Network properties can be displayed simultaneously with the training data or test data in the same input space. Principal component analysis is used to transform the input data so that its most salient dimensions can be visualized. This method also allows changes made while graphically editing the network structure, in transformed space, to be projected back into the original input space.

Design and Control of Large Collections of Learning Agents. This research focuses on the problem of designing groups of autonomous agents that individually learn sequences of actions such that the resultant sequence of actions achieves a predetermined global objective. We are particularly interested in instances of this problem where centralized control is either impossible or impractical.

For single agent systems in similar domains, machine learning methods (e.g., reinforcement learners) have been successfully used. However, applying such solutions directly to multi-agent systems often proves problematic, as agents may work at cross-purposes, or have difficulty in evaluating their contribution to achievement of the global objective, or both. Accordingly, the crucial design step in multi-agent systems centers on determining the private objectives of each agent so that as the agents strive for those objectives, the system reaches a good global solution. In this work we consider a version of this problem involving multiple autonomous rovers, where the global objective is to maximize the aggregate information collected by that set of rovers. We employ concepts from collective intelligence to design the goals for each rover. In this work we focus on the problem of designing groups of autonomous agents that individually learn sequences of actions such that the resultant sequence of joint actions achieves a predetermined global objective. We tackled the problem of controlling multiple planetary exploration vehicles (e.g., Rovers on the surface of Mars) such that their collective behavior maximizes the total information collected. In this domain, we addressed the critical issue of what utility functions those agents should strive to maximize using COIN theory. Previous applications of COIN theory focused on maximizing rewards (i.e., single time step utility values) rather than time-extended utilities. In this work we extend these results to a problem where agents need to take sequences of actions, and use the Q-learning with utilities derived from COIN theory. Our results demonstrate that RL rovers using COIN-derived goals outperform both "natural" extensions of single agent algorithms and global reinforcement learning solutions based on "team games." Currently we are considering macro-learning techniques which involves learning other than each agent's reinforcement optimization of its private utility. Also we are studying learning under a variety of communication restrictions e.g. being able to observe only a subset of the other agents. Breakthroughs in both areas will make this approach applicable to a wide range of DoD problems involving mutiple agent systems.

Global Optimal Surface from Stereo. We have developed an effective global optimized stereo matching approach that produces a dense displacement map and an occlusion map [23]. The global

matching cost and various constraints, including matching uniqueness and ordering, and local smoothness along and across epipolar lines, are all cast into a novel configuration of a maximum flow graph. The correspondence between the associated minimum cut and the defined stereo problem guarantees a global optimized disparity solution confined by those geometric constraints, while still preserving discontinuities. Different similarity measures can be applied to this framework to deliver more reliable matching results. The capacities of the edges, which model the smoothness and occlusion, depend on the quality of the input images and the particular structure of the surface. An intuitive way is to use the edge and junction maps as a cue to adapt these capacities to the area discontinuity, since occlusion and discontinuities are more likely to occur in the presence of edges and junctions. More sophisticated area analysis or segmentation will help the computation of the smoothness arc capacity and improve the depth estimation. A multiple resolution approach can be directly embedded into the graph to reduce the computational complexity.

Blind Image Deconvolution. In this project, we addressed the problem of blind image deconvolution, where neither the image received nor the degrading systems (assumed LTI) are known [24-27]. This problem is of high interest for applications such as imaging objects from the air, imaging objects in the air from the ground, and other applications where there is little known about the degrading channel or system. We assume that multiple blurred versions of the image are available. The blurs are assumed to be different, e.g., taken at different times through a turbulent medium. This problem is called multichannel blind deconvolution. We solved a nullspace-based multichannel blind image restoration problem using matrix operations. We posed the problem as a constrained optimization problem. By using different constraints, different optimization problems were formulated. One of these can be solved by matrix operations alone.

The formulation of the different optimization problems implies a new column-space-based algorithm. The restored images by this new algorithm and a nullspace-based one are the same. This new algorithm has the same advantages as the nullspace-based one, such as exact restoration and no noise amplification. Furthermore, the new algorithm requires much less computational complexity than the nullspace-based one. Actually, under some mild conditions, the complexity of this new algorithm is equal to FFT complexity.

Another eigenstructure-based direct multichannel blind image restoration algorithm is direct deconvolver estimation. We also formulated it as an optimization problem. We made a connection between it and the new algorithm. By using a different constraint and putting some weighting on the objective function of the optimization problem, the direct deconvolver estimation approach is shown equivalent to the new algorithm.

We thoroughly studied eigenstructure-based techniques for direct multichannel blind image restoration. The LTI FIR model was used and the size of the blur channels was assumed in these techniques. These limitations should be removed in the future. Further, we should move to solve nonlinear and/or non-time-invariant problems.

Publications

a. Papers published in peer-reviewed journals

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b. Papers published in conference proceedings

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c. Manuscripts submitted but not published

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d. Other publications.

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None.

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